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The eastern Black Sea-Caucasus region during the Cretaceous: New evidence to constrain its tectonic evolution

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We report new observations in the eastern Black Sea-Caucasus region that allow reconstructing the evolution of the Neotethys in the Cretaceous. At that time, the Neotethys oceanic plate was subducting northward below the continental Eurasia plate. Based on the analysis of the obducted ophiolites that crop out throughout Lesser Caucasus and East Anatolides, we show that a spreading center (AESA basin) existed within the Neotethys, between Middle Jurassic and Early Cretaceous. Later, the spreading center was carried into the subduction with the Neotethys plate. We argue that the subduction of the spreading center opened a slab window that allowed asthenospheric material to move upward, in effect thermally and mechanically weakening the otherwise strong Eurasia upper plate. The local weakness zone favored the opening of the Black Sea back-arc basins. Later, in the Late Cretaceous, the AESA basin obducted onto the Taurides–Anatolides–South Armenia Microplate (TASAM), which then collided with Eurasia along a single suture zone (AESA suture).

1. Introduction

The Black Sea and Caucasus regions (Fig. 1) have a complex geological history (Adamia et al., 1981, 2011; Barrier and Vrielynck, 2008; Dercourt et al., 1986; Finetti et al., 1988; Khain, 1974; Nikishin et al., 1998, 2015; Robinson et al., 1996; Saintot and Angelier, 2002; Saintot et al., 2006; Stampfli et al., 2001; Stephenson and Schellart, 2010; Zonenshain and Le Pichon, 1986), which is well attested to by their contrasting topography: while the Black Sea is a 2245-m-deep "marine" basin, the Caucasus is a mountain belt with peaks as high as 5642 m (in the

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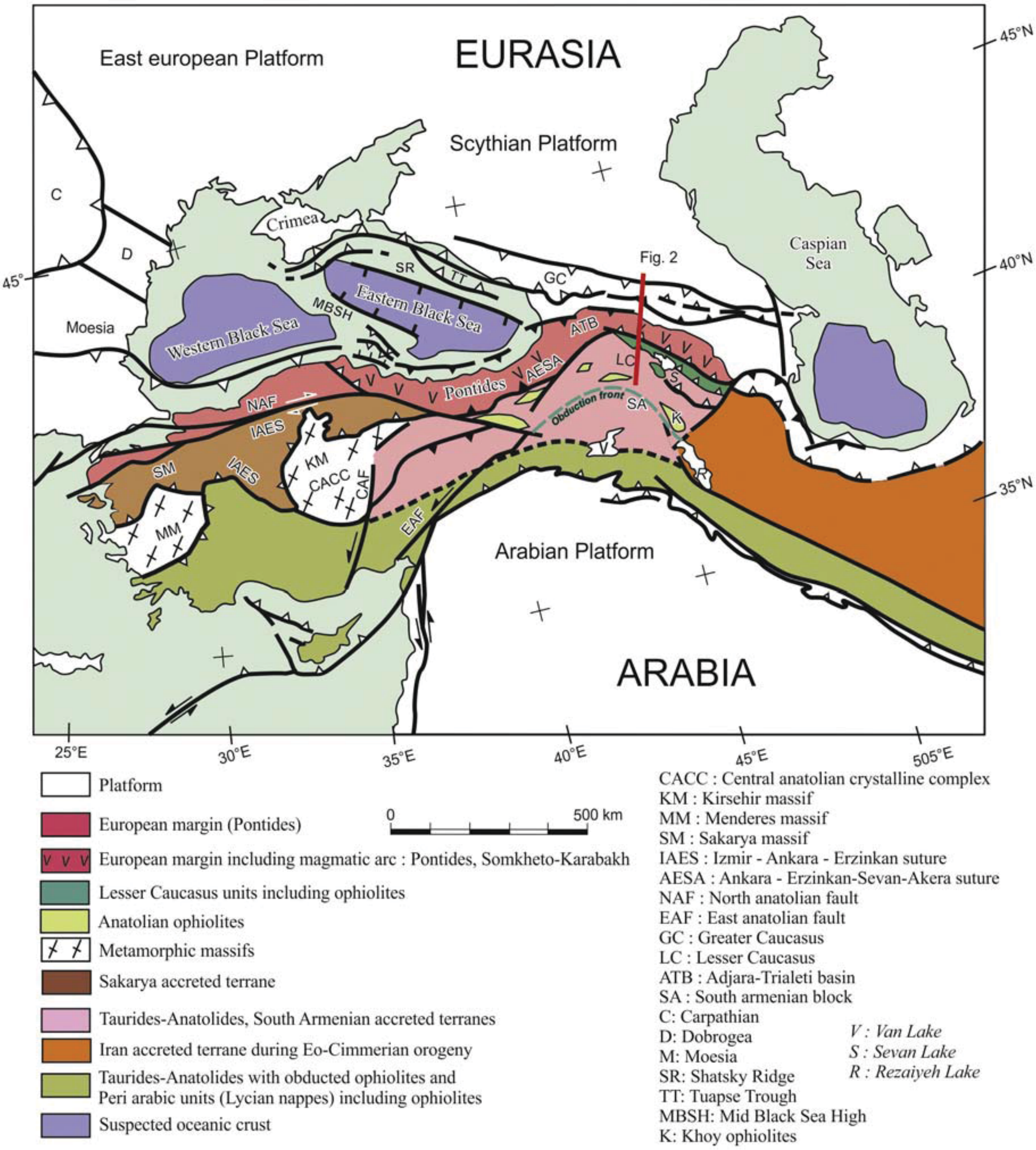

Fig. 1. Structural sketch map of the Black Sea-Caucasus region in the general framework of the Middle East.
Modified from Sosson et al., 2010.

Greater Caucasus). This makes the region overall a landmark feature of Eurasia (Forte et al., 2010, 2013; Mosar et al., 2010; Ross et al., 1974; Starostenko et al., 2004). The Black Sea and Caucasus belong to the Alpine belt (s.l.) and their formation is related to the closure of the Neotethys Ocean (Barrier and Vrielynck, 2008; Dercourt et al., 1986; Stephenson and Schellart, 2010; Zonenshain and Le Pichon, 1986). The northward subduction of the Neotethys oceanic plate under the Eurasian continental plate is attested to by the arc-type magmatic products that are found on the Eurasian southern margin from Moesia in the west to the Lesser Caucasus in the east, passing through Crimea and Pontides (Fig. 1; Adamia et al., 1981; Lordkipanidze et al., 1989; Meijers et al., 2010; Okay and Nikishin, 2015; Robinson et al., 1996). Subduction started in the Middle Jurassic. The Neotethys oceanic plate was entirely subducted from Late Cretaceous to Early Paleocene in the east (region of Lesser Caucasus; Hässig et al., 2015; Rolland et al., 2012; Sosson et al., 2010) and from Paleocene to Eocene in the west (region of Pontides;

Espurt et al., 2014; Lefebvre et al., 2013; Okay and Nikishin, 2015; Robertson et al., 2014; Sengör et al., 2003). From these times on, the northward convergence of the Neotethys plate led to the collision of continental microplates (two principal "continental blocks", the Taurides–Anatolides–South Armenia Microplates or TASAM, and the Kirsehir block) with the Eurasian plate (Fig. 1). Therefore, the subduction process of the Neotethys oceanic plate has been operating for about 100–120 million years. Such a long duration is supported by the reconstruction of the Neotethys domain derived from paleomagnetic and paleogeographic data (e.g., Barrier and Vrielynck, 2008). These reconstructions additionally suggest that in late Early Jurassic (Toarcian), the approximate oceanic plate width between Gondwana and Laurasia was at most 3000 km. The long-living subduction process is also attested to by the tomographic images that were obtained beneath Eurasia and Anatolia. These images reveal an important accumulation of cold lithosphere on the top of the lower mantle and within it (at a depth from 500 to 660 km; Faccenna et al., 2006; Lei and Zhao, 2007; Spakman, 1991; Zor, 2008), which is interpreted as a remnant of the Neotethys slab. The Neotethys slab would thus have sustained break off.

During the long Neotethys subduction process, several domains formed in back-arc positions within the Eurasia Plate, mainly the Greater Caucasus basin that opened in Early–Middle Jurassic (no oceanic crust was formed however; Adamia et al., 1981, 2011; Barrier and Vrielynck, 2008; Dercourt et al., 1986; Khain, 1974), and the western and eastern Black Sea basins that opened during the Cretaceous and/or Cenozoic (Yegorova and Gobarenko, 2010; Cloetingh et al., 2003; Finetti et al., 1988; Khriachtchevskaia et al., 2010; Letouzey et al., 1977; Okay et al., 1994, 2013; Robinson et al., 1996; Spadini et al., 1996; Stephenson and Schellart, 2010; Vincent et al., 2005; Zonenshain and Le Pichon, 1986). Various scenarios have been proposed to explain the opening of the Black Sea basins (e.g., Okay et al., 1994, 2013; Stephenson and Schellart, 2010), but their origin is still unclear. One reason is that the nature of the Black Sea is not so well understood. Why was the Black Sea preserved as a basin in a region that everywhere sustained compression and collision from the Late Cretaceous to the Eocene?

We argue here that the Cretaceous period holds some of the information that is needed to understand the Black Sea's origin and evolution. We thus focus on this period.

In the last decade, major research programs (such as MEBE: "Middle East Basins Evolution" and DARIUS) have been launched to acquire new data on stratigraphy, tectonics, paleomagnetism, petrology, geochemistry, geochronology, deep Earth structure (seismic images), and in that framework, our group worked especially in the region north of the eastern Black Sea Basin (Crimea), in the Greater Caucasus (Georgia and Azerbaijan), and in the Lesser Caucasus (Armenia, Azerbaijan and Georgia). The new data and results have significantly upgraded our knowledge of the tectonic evolution, geodynamic processes and the timing and style of deformation. We sum up some of these new results here, and we use them along with prior knowledge to propose reconstruction scenarios of the Neotethys domain, with particular attention to the opening of the Black Sea.

2. New insights from studies of ophiolitic units

Ophiolites along the present suture zone that marks the closure of the Neotethys ocean (the "Ankara–Erzincan–Sevan–Akera suture zone" or AESA, Fig. 1) attest to the existence of a back-arc basin (the "AESA basin") within the northern branch of the Neotethys (e.g., Hässig et al., 2013b and Robertson et al., 2014 for a review). The AESA basin formed from Middle Jurassic to Late Cretaceous above and as a result of an intra-oceanic subduction zone within the Neotethys (Rolland et al., 2009a, 2010; Sosson et al., 2010). That intra-oceanic subduction was dipping north.

More recently in the Lesser Caucasus, our further analyses of the ophiolitic units along the AESA suture have revealed the existence of ophiolites of Jurassic age at many sites along the suture. These Jurassic ophiolites are magmatic rocks of back-arc geochemistry tendencies (E-MORB), covered by OIB of Early Cretaceous age (Galoyan et al., 2009; Hässig et al., 2014; Robertson et al., 2014; Rolland et al., 2009b, 2010). We also found radiolarites and pelagic carbonates mixed with the ophiolites. Those have a Middle Jurassic to Late Cretaceous age (Danelian et al., 2012, 2014, 2015). They overlie ultrabasic, basic, and plagiogranitic rocks, and some of them are interbedded with basaltic and volcanoclastic layers. These additional findings suggest that the back-arc oceanic basin remained well preserved from the Mid Jurassic to the Late Cretaceous interval.

From Anatolia to the Lesser Caucasus and then to NW-Iran, ophiolitic units attributed to the oceanic back-arc basin form a 700-km-long and 200-km-wide nappe. These now obducted ophiolites have an age of 150–170 Ma (Avagyan et al., 2015; Çelik et al., 2011; Galoyan et al., 2009; Hässig et al., 2013a, 2013b; Rolland et al., 2009a; Sosson et al., 2010; Topuz et al., 2013a, 2013b). This age is found similarly along the 700-km-long ophiolitic zone, which suggests that the oceanic crust was formed from a spreading center whose axis was parallel to the intra-oceanic subduction zone (Hässig et al., 2015), and hence likely trending NW–SE. As said earlier, we also found evidence for large amounts of Lower Cretaceous OIB magmatism. Hässig et al. (2015) have suggested that this important magmatism might have warmed the existing Middle Jurassic oceanic lithosphere of the back-arc Basin, which in turn possibly modified its rheological and mechanical properties.

Taken together, these results therefore suggest that, south of Eurasia, in the northern Branch of the Neotethys, an intra-oceanic north-dipping subduction was operating from the Middle Jurassic to the Late Cretaceous and induced the opening of a back-arc basin (the AESA basin) floored with oceanic crust. The present AESA suture zone marks the closure of both the Neotethys and its internal AESA back-arc basin. It seems that significant intraplate magmatism (hot spots or oceanic plateau) occurred in the Early Cretaceous, and reheated the southern part of the AESA back-arc basin, possibly modifying its mechanical properties (Okay et al., 2013; Rolland et al., 2009a).

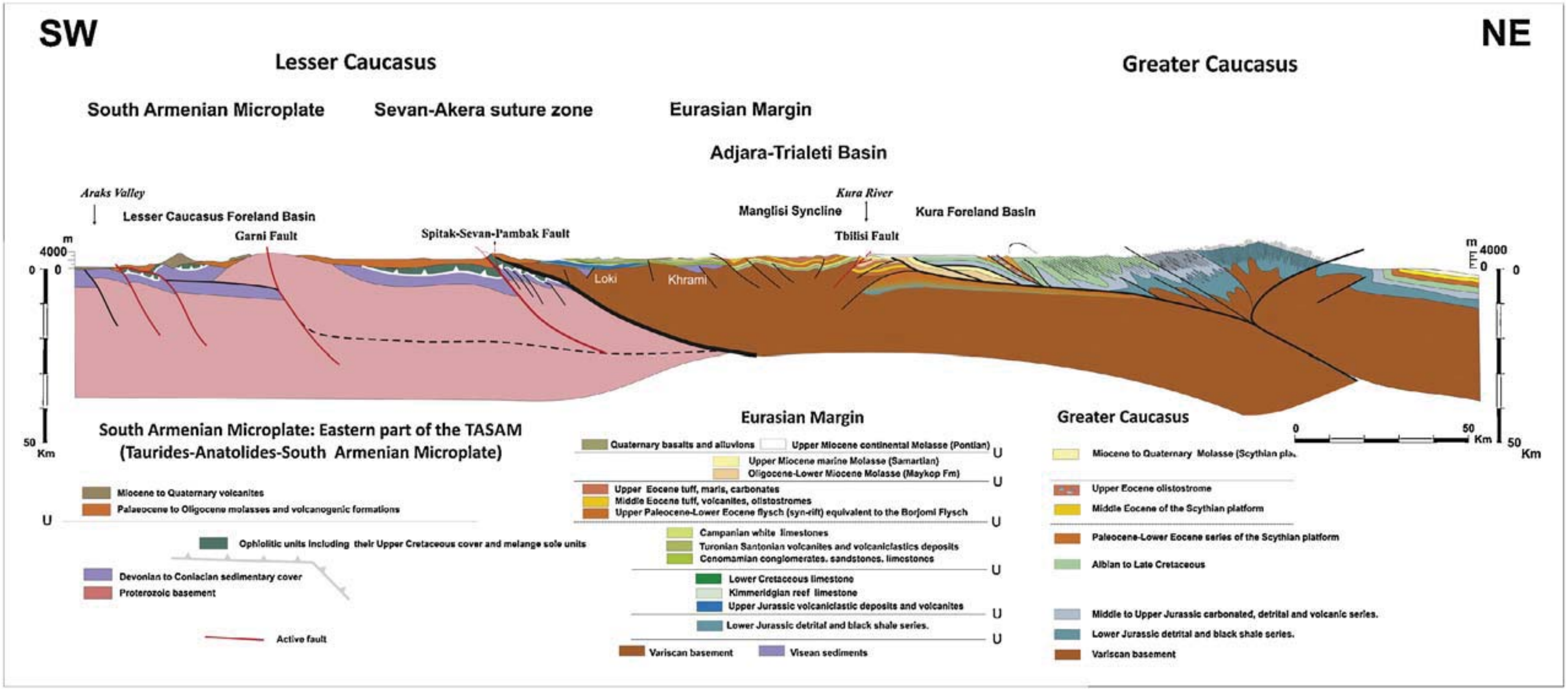

Fig. 2. Crustal section across the Greater and Lesser Caucasus (see location on Fig. 1). Active faults in Lesser Caucasus are from Avagyan et al. (2005, 2010). Ophiolites are obducted over the southern Armenian Microplate over a minimum distance of 120 km. The schistosity in the inner part of the Greater Caucasus is indicated on the section (unpublished results from our group).

3. A new transect through the Greater and Lesser Caucasus

To better understand the evolution of the Black Sea–Caucasus region during the Cretaceous, we built a 400-km geological transect that crosses the AESA suture zone (Fig. 2). Observations along this transect reveal the following points:

- Middle Jurassic to Upper Cretaceous arc-related volcanites are well exposed on the transect, all along the Eurasian margin (Fig. 2; Adamia et al., 1981; Sosson et al., 2010);
- the obduction of the AESA back-arc basin onto the Taurides–Anatolides–South Armenia Microplate (TASAM) occurred since the Cenomanian (Danelian et al., 2014) and continued for part of the Coniacian–Santonian interval (88–83 Ma; Sosson et al., 2010). This obduction followed a period when the oceanic lithosphere of the AESA basin was reheated by subsequent magmatism (Hässig et al., 2013a, 2013b, 2014, 2015);
- soon after the obduction ($\sim$83 Ma), the north–south distance between the eastern TASAM (of Gondwanan origin) and the Eurasian margin was at most 1000 km (Meijers et al., 2015). Therefore, remnants of the oceanic AESA Basin still existed between TASAM and Eurasia during the Late Cretaceous (Fig. 2);
- the collision of TASAM with Eurasia occurred between the Latest Cretaceous and the Mid Eocene (74–40 Ma) (Rolland et al., 2010, 2012; Sosson et al., 2010). This is especially evidenced by the pronounced late Middle Eocene unconformity that is found in the two continental plates and in the suture zone (Figs. 2 and 3);
- only one suture zone exists in the Lesser Caucasus whose eastward continuation extends in the Anatolides (Hässig et al., 2013a, 2013b; Sosson et al., 2010) (Fig. 2). The suture section in the Lesser Caucasus belongs to the AESA suture zone. Therefore, it is genetically related to the northern branch of the Neotethys;
- the foreland basins of the Lesser and Greater Caucasus can also be observed along the transect (Fig. 2). They are of Paleocene–Miocene age and result from the definitive closure of the Neotethys, which was marked, first by the collision of the continental TASAM with Eurasia, then by the collision of Arabia with Eurasia (Fig. 2). Observations along the transect show that:
  - erosion started in the Eocene in the Greater Caucasus (e.g., Mosar et al., 2010),
  - the Paleocene–Eocene Adjara–Trialeti basin within the Eurasian margin was tectonically inverted during Oligo-Miocene,
  - deformations further north started later, in the Late Eocene, and from then on, migrated northwards from the Lesser Caucasus to the Greater Caucasus (Adamia et al., 2011, 2015; Alania et al., 2015) (Fig. 2).

In the following, we will use these new results as a basis to discuss the relationships between Neotethys and Eurasia in the Caucasus region during the Cretaceous.

4. Rifting characteristics in eastern Black Sea Basin

The Black Sea basin is classically interpreted as a back-arc basin that formed within the Eurasian plate on top of the Neotethys subduction (Cloetingh et al., 2003;

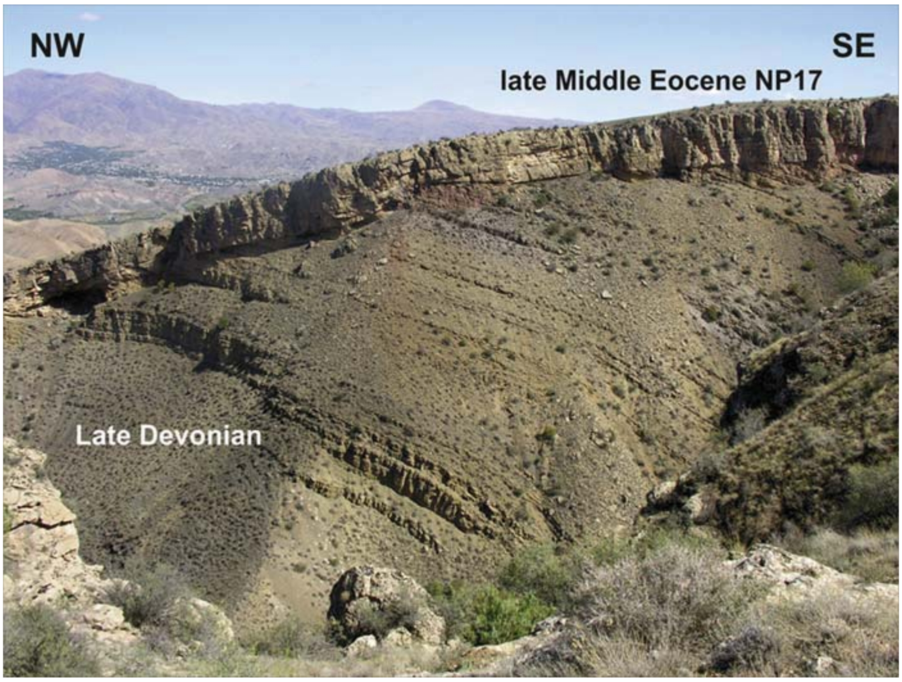

Fig. 3. Photography of the late Middle Eocene unconformity on top of the folded Upper Devonian series from the southern Armenia Microplate (Arpi region, Armenia). This unconformity is found throughout Eurasia, suture zone and Taurides–Anatolides–South Armenian Microplate (TASAM) (see cross section on Fig. 2).

Okay et al., 1994; Robinson et al., 1996; Spadini et al., 1996). Rifting is considered to have initiated in Early–Middle Cretaceous (Görür, 1988; Finetti et al., 1988; Hippolyte et al., 2010; Nikishin et al., 2013, 2015; Stephenson and Schellart, 2010) or Paleocene–Eocene (Cloetingh et al., 2003; Robinson et al., 1996). Another common assumption is that rifting was induced by slab roll back (Stephenson and Schellart, 2010), and occurred along an axis parallel to the subduction zone, i.e., about east–west (Barrier and Vrielynck, 2008; Stephenson and Schellart, 2010; Fig. 4). However, the NW–SE normal faults that formed during the rifting of the eastern Black Sea (Görür, 1988; Nikishin et al., 2010; Stovba et al., 2013) have a trend that is not consistent with the orientation of the subduction zone. Furthermore, recent observations in the Crimean Mountains have revealed the existence of north–south to NNW–SSE-trending normal faults of Early Cretaceous age, and hence likely related to the eastern Black Sea rifting (Hippolyte et al., 2014; Sheremet et al., 2014, 2015). Therefore, rifting in the eastern Black Sea occurred along an axis that was oblique to the subduction trench.

5. Paleotectonic reconstruction of the Black Sea-Caucasus region during the Cretaceous

Taking into account the observations presented above, we propose a scenario that describes the tectonic evolution of the Black Sea–Caucasus region during the Cretaceous (Fig. 4). In Late Jurassic–Early Cretaceous times (Fig. 4, Tithonian and Aptian), the Eurasia continental lithosphere plate was rheologically strong (Cloetingh et al., 2003; Stephenson and Schellart, 2010), bounded to the south by an active subduction zone, allowing the Neotethys oceanic plate to subduct northward below Eurasia. A secondary intra-oceanic subduction zone was active within the Neotethys plate, and this intra-oceanic subduction induced the opening of the AESA back-arc basin. That basin was then led progressively into subduction beneath the Eurasia plate. As a result, the NW–SE-trending spreading center of the back-arc basin was also subducted beneath Eurasia. The oceanic spreading center moved along and entered in the trench progressively from west to east. Southward, the Middle Jurassic lithosphere of the AESA basin was reheated by hot spot and/or oceanic plateau magmatism (Fig. 4, Aptian).

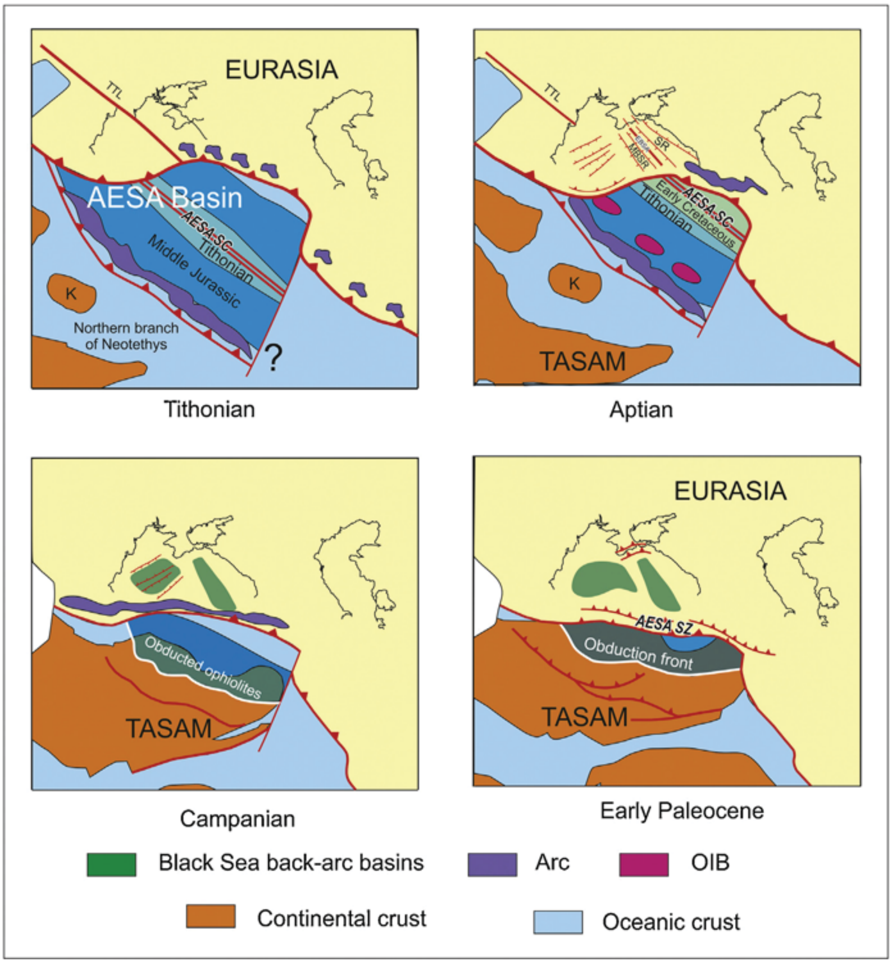

Fig. 4. Reconstruction of the Back Sea-Caucasus region from the Tithonian to the Early Paleocene. AESA: Ankara–Erzincan–Sevan–Akera basin; TASAM: Taurides–Anatolides–South Armenian Microplate; K; Kirsehir block; SR: Shatski Ridge; MBSR: Middle Black Sea Ridge; EBSA: Eastern Black Sea Axis; AESA SC: Ankara-Erzincan–Sevan–Akera spreading center; AESA SZ: Ankara-Erzincan–Sevan–Akera Suture Zone; TTL: Tornquist–Teisseyre Line.

In this scenario, the question remains as to what geodynamic processes might have produced the opening of the Black Sea basins during the Early Cretaceous.

Stephenson and Schellart (2010) have suggested that the opening of the Black Sea basins might have resulted from an asymmetric counterclockwise slab roll back; this would open an asymmetric back-arc basin within a strong lithosphere, and explain the opening of the western Black Sea basin before that of the eastern Black Sea basin. But, this scenario, as many others, does not take into account the thermal particularities of the subducting Neotethys plate.

Therefore, we suggest here that the opening of the Black Sea was enhanced by the subduction of the AESA spreading center. There is no evidence of relics of spreading center rock assemblages in the ophiolitic nappe obducted onto TASAM, which implies that the AESA spreading center subducted entirely beneath Eurasia. The subduction of a spreading center has important consequences, especially in that it opens a "window" into the subducting slab (e.g., Dickinson and Snyder, 1978; Groome and Thorkelson, 2009; Thorkelson, 1996). The slab window allows upward motion of asthenospheric material, which, in turn, may increase the temperature in the upper lithospheric plate, and weaken the upper plate both thermally and mechanically. In these conditions, the slab retreat would have occurred more easily behind the weakened upper plate (Billen, 2008; Thorkelson, 1996), as shown in kinematic and thermo-mechanical models (Billen, 2008; Groome and Thorkelson, 2009). We thus suggest that the subduction of the AESA spreading center was the major factor, which induced the opening of the Black Sea. The orientation of the subducted ~NW-trending AESA spreading axis well explains the trend of the rifting axis of the eastern Black Sea, as the trend of the normal faults which bound the Shatsky ridge (Fig. 1) and the orientation of the Mid-Black Sea High (Fig. 1), both are relics of a Jurassic platform that was disrupted during the rifting. All these features related to the eastern Black Sea rifting are oblique to the trench. Additional evidence exists for the subduction of the AESA spreading center; most were described by Okay et al. (2013) and Hippolyte et al. (2015) in the Pontides:

- a gap in magmatic arc activity in Early Cretaceous;
- a Lower Cretaceous low-grade metamorphism event in central Pontides (Çangaldağ Complex);
- the uplift and erosion of the Pontides after the Hauterivian (during the Mid Cretaceous).

The first two points reveal the existence of thermal anomalies (absence of arc magmatism and high temperature metamorphism), as expected in a plate immediately above a slab window (e.g., Groome and Thorkelson, 2009; Thorkelson, 1996). Uplift is also consistent with the mechanical response of a warmed upper plate. The Pontides region thus holds the potential to reveal further evidence of the subduction of the AESA spreading center.

Our observations and interpretations therefore suggest that the Late Cretaceous was a time of profound changes in the Black Sea-Caucasus region (Fig. 4, Campanian). The major "events" included:

- in the south, the northward subduction of the Neotethys beneath Eurasia;
- the reheating and hence weakening of the Middle Jurassic AESA back-arc basin lithosphere by subsequent hot spot or plateau magmatism during Early Cretaceous.

This weakening favored the obduction of the AESA Basin onto TASAM (Fig. 4, Campanian). Later, the oceanic lithosphere remnants located further south disappeared in the northern subduction zone, up to a time when the collision started between TASAM and Eurasia (from Latest Cretaceous to Eocene, from east to west, respectively; Fig. 4. Early Paleocene; e.g., Robertson et al., 2014; Sosson et al., 2010).

6. Conclusion

Along with prior results, the new observations we have reported here allowed us to propose a novel scenario for the Neotethys domain in the Cretaceous and its subduction below the continental Eurasia plate. A major feature of this scenario is the existence, well documented in the obducted ophiolites that are found in the Lesser Caucasus and the East Anatolides, of a spreading center, the AESA basin, within the Neotethys. Later, the spreading center was carried into the subduction of the Neotethys. We argue that the subduction of the spreading center produced a slab window that allowed the asthenospheric material to move upward, in effect weakening thermally and mechanically the Eurasia upper plate. The existence of a local weakness zone within the otherwise strong Eurasia plate favored the opening of the Black Sea back-arc basins. Later, during the Late Cretaceous, the AESA basin obducted onto the TASAM microplate. Then the collision of TASAM occurred with Eurasia, altogether mixing the two source-ophiolites into a single suture zone (the AESA suture) between TASAM and Eurasia.

The new reconstruction of the Neotethys in the Cretaceous that we propose should be taken into account in the future, more global paleoreconstructions of the entire Tethys Realm. Furthermore, the possibility of a slab window should to be taken into account in thermo-mechanical modeling of the Black Sea opening.

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